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MODELLING THE ECONOMICS OF RAIL TERMINAL OPERATIONS IN GRAIN TRANSPORTATION: A BRAZILIAN CASE STUDY

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Abstract

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Modelling the Economics of Rail Terminal Operations in Grain Transportation: A Brazilian Case Study

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Transportation costs are decomposed into line-haul costs and terminal costs. Physical handling efficiency at terminals decreases overall transportation costs and augments service capacity. A capacitated network model is used to apply this general concept to rail transportation bottlenecks on a Brazilian export corridor.

"Modelling the Economics of Rail Terminal Operations in Grain Transportation: A Brazilian Case Study"*

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Introduction

The tremendous increase in production of soybeans and other grains in southern Brazil during the last five years has created transportation bottlenecks along export routes. This paper examines one aspect of the problem: the efficiency of rail terminal operations in the port of Paranaguá. The port serves the Paraná export corridor, including parts of three Brazilian states and the Republic of Paraguay. A capacitated network model is used to quantify the costs of the existing terminal bottleneck and to simulate improvements. In this manner it is possible to relate: (1) physical handling ability to costs of service and availability of cars to grain shippers; (2) terminal costs to overall costs of rail service; and (3) cost components to appropriate charges for rail service.

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A Model of Transportation Costs

Standard economic analysis assumes that the most economic mode of transportation is determined, in large part, by the distance of the shipment. Typically, the cost structure is defined as in Figure 1 where small trucks are least expensive for shipping a commodity over distances up to OA; large trucks for distances from OA to OB; rail for distances OB to OC; and water for distances greater than OC. The graph reflects the relative cost structures of these modes in many parts of the world in recent decades. Superficially considered, Figure 1 provides graphic evidence for the widespread belief that railroads are economical only for long hauls.

It now appears that this assumption about cost structure is inappropriate. Sward's study for a Minnesota rail line reveals that transport costs can be much more closely related to terminal efficiency than to distance *per se*. Through a meticulous time-motion-cost study, Sward demonstrated that improved terminal operations reduced car ownership costs per gross ton from $3.25 to $0.15 on the line, and that continued improvements in terminal operations could lower this cost to $0.06 (pp. 31-34).

Sward's pioneering study provides an empirical base for the development of an economic model with wide applicability in transportation economics. The central concept is that the least expensive mode in Figure 1 is determined by two distinct cost components: (1) line haul costs, which increase linearly with distance; and (2) terminal or turn-around costs, which increase with time rather than distance.

Line haul costs are composed primarily of capital costs (interest on investment and physical wear), fuel, lubricants and oil, and labor.

Turn-around costs, on the other hand, are basically a function of time and include labor, the interest on the investment in rolling stock and loading/unloading equipment. Also included are "overhead" items such as administration, license fees and insurance. Several of these items may also be considered line haul costs. They vary, however, with the time spent on the line haul rather than the distance traveled.

A very high percentage of railroad costs are related more closely to time than traffic. Administration, terminal employees, rolling stock and maintenance of the permanent way involve cost items which rise less than proportionately with increases in traffic. Conversely, railroads have tremendous cost advantages over trucks with respect to some line haul costs such as salaries and fuel. An engineer and brakeman replace 272 truck drivers each with a truck of 25 net tons if each car in an eight car train holds 85 tons; trains are several times more fuel efficient than trucks on loads of heavy bulk items. Therefore, greater physical efficiency in terminal operations can significantly reduce turn-around times, thus lowering total shipping costs and shifting traffic from road to rail (if prices accompany declining costs). This concept is illustrated graphically in Figure 2, where a reduction in terminal costs from OR to OR' enables the railroad to capture traffic of distances OF-OG formerly held by trucks. Cost savings are realized for all distances greater than OF up to a maximum of BC (=RR') for OG or more kilometers.

The above analysis implies that railroads can be economical on short as well as long hauls, if large volumes of bulk-handled commodities permit efficient terminal operations. A more subtle point is that for a fixed supply of rolling stock, more efficient terminal operations increase the total capacity of the rail system. The less time rail cars and locomotives spend in terminals, the more time they can actually transport commodities. This point is dramatically illustrated by the recent experience of Parana's export corridor.

The Paraná Export Corridor

Figure 3 provides a sketch of the road and rail system of Paraná, presently Brazil's major soybean producing state. Paraná's export production, as well as some of that from the neighboring states and Paraguay, must pass through this system. The roads shown are paved two-lane rural highways. Grain traffic saturates these roads, damages pavement, causes congestion for other users, and is generally more expensive to grain shippers than rail transport. Truck transportation is extensively used for grain shipments in the area, however, due to lack of rail capacity. The inadequacies of the rail infrastructure are substantial: narrow gauge (1 meter), sharp curves, light rails, excessive grades and others. The mountain substretch of the Ponta Grossa-Paranaguá line is especially difficult, with a minimum radius of only 90 meters for some curves and grades of 3% (Ministério dos Transportes et al., Quadro 6).[2]

The port terminal of Paranaguá, in contrast, is now equipped to handle large ocean vessels (up to 65,000 metric tons) and has one of the world's largest grain loading capacity of 5,100 metric tons/hour (APPA). Paradoxically, however, the port rather than the rail lines is the major bottleneck in Paraná's present grain transport system. This is due to the inefficient rail terminal operations.

The rail terminal problem begins in the interior of the state where trains are assembled from diverse shippers (generally shipments of pellets from soybean processors), rather than in trainload volume shipments from a single customer.[3] Once in the port terminal, trains must be broken down, sent to different receivers within the terminal, weighed, unloaded and reassembled.[4] They also compete with trucks for unloading space. Railcars and locomotives are typically tied up from two to three days in these operations, plus a minimum of one day in the interior terminals This is a total of 84 hours of terminal delay on each round trip. This compares with 50 hours of line haul time for Maringá-Paranaguá round trip (the longest shipment considered here). Congestion in the port is thus seen to be the primary cause of the widespread lack of rail cars for grain shipments.

The Problem Viewed as a Capacitated Network

As Bradley states, network models offer four substantial advantages in relation to other optimizing techniques:

(1) flexibility (accurate modeling of many situations);

(2) ease of use and interpretation;

(3) low cost solutions (100-300 times faster than linear programs for many problems); and

(4) ability to solve problems with more variables and constraints than any other optimization method.

The low cost solution under many constraints makes the network formulation a superior approach to the problem. Equally important, however, is the ease with which the capacity constraints and other features of the actual Paraná export corridor system may be represented. This is illustrated in Figure 4. Nodes such as RI_1 and SI_1 represent facilities or points in the system. They are joined by directed arcs indicating the direction of permissible flows. Each arc has three parameters (for simplicity only a few are assigned in the diagram): (1) a cost C_{ij} of transporting a unit of flow from node i to node j; (2) an upper limit (U_{ij}) on the units which may flow from i to j; and (3) a lower limit (L_{ij}) on the units of flow from i to j.

Production in time period 1 in any exporting microregion is indicated by flow from the artificial "source" DO over an arc such as (DO,SI_1), where SI_1 is a storage unit in the microregion in period 1. All grain must pass through these units for cleaning and drying. The zero cost on the arc indicates that production costs are not included in the model, and the value U_p is the microregion's exportable surplus, estimated exogeneously. Grain in the storage unit SI_1 may be stored until the next time period, or shipped by rail or truck to the port. Storage is represented by flow over arc(SI_1, SI_2), where SI_2 is the same storage unit in time period 2 and the storage capacity is given by U_s, the upper limit on the arc.

The rail and truck loading operations are given by flows over (SI_1, RI_1) and (SI_1,TI_1) for transportation in the first period. The rail and truck line hauls are represented by flows over arcs (RI_1,PRT_1) and (TI_1,PTT_1). Although the intermediate nodes (intersections, other cities etc.) are omitted from the diagram for simplicity, they are of course included in the model and represent a straightforward extension of the graphic analysis.[5]

The rail and truck terminal operations are represented by flows over arcs(PRT_1,PS_1) and (PTT_1PS_1). The upper limit on the rail terminal arc represents, in effect, a constraint on rolling stock, since terminal delays resulted in inability to provide potential users with rail cars. Once in the port storage units (PS_1), grain may be stored into the next time period or loaded onto ships, represented by arcs(PS_1,PS_2) and (PS_1DD), respectively. The lower limit L_{d1} on the latter arc represents the exogeneously estimated export demand in period 1.

The model outlined in Figure 4 thus represents the essential features of the Paraná export corridor system: production and storage, truck and rail transportation (divided into terminal and line haul components) and seasonal demands for export. Soybean crushing is also represented in the model, although it has been omitted from the diagram for simplicity. The complete problem includes 34 producing microregions, 44 highway nodes, 10 rail nodes, 10 processing plant locations and 4 time periods (only two are shown in the diagram).

There are two models, representing (1) the basic transfer system as it existed in 1976, and (2) the basic system with an improved rail terminal in Paranaguá. The improved terminal would have separate reception areas for corn, soybeans and meal, and each train could be unloaded in 10 hours or less with minimum switching operations.

In each model, an optimal solution is obtained using the Fulkerson algorithm for capacitated networks (Fulkerson; Potts and Oliver, Ford and Fulkerson).[6] The algorithm determines the maximum set of flows X_{ij} so as to minimize the total transfer costs including terminal, line haul, storage and other costs assigned to the arc. In this case, the maximal flow equals the available supply from all exporting microregions, and is allocated to the least cost arcs.

The algorithm minimizes

(1) $\Sigma C_{ij}X_{ij}$ for all i and j

subject to

(2) $L_{ij} \leq X_{ij} \leq U_{ij}$ for all i and j

and

(3) $\sum_j X_{ji} - \sum_j X_{ij} = 0$ for all i

where

C_{ij} is the unit cost of shipment from i to j (Cr\$/ton)

X_{ij} is the quantity shipped from i to j (tons)

L_{ij} is the lower limit on shipment from i to j (tons)

U_{ij} is the upper limit on shipment from i to j (tons)

Condition (3) is the conservation of flow principle that the total flow into a node must equal the total flow out of it.[7]

The solution values for the rail terminal arcs in Paranaguá are given in columns 1-7 of Table 1. The C_{ij} value of Cr\$29/ton is the estimated cost of the terminal operation at present with the typical 60 hour delay. The CBAR values are the net arc costs, defined as:

(4) $\overline{C}_{ij} = C_{ij} - (p_j - p_i)$

where p_j is the destination price and p_i is the origin price. If (p_j-p_i) exceeds the transfer cost C_{ij}, the net arc cost is negative. This implies that a negative cost, or savings, is available to the system for each additional unit of flow going over the arc and thus avoiding more expensive paths in the system. Optimality requires that any arc with a negative value be used to upper capacity, so that $X_{ij} = U_{ij}$ on these arcs. Such arcs are the bottlenecks in the system, and the CBAR values are the savings available from a unit increase in their capacities. In Table 1 (part a), the rail terminal operates at capacity in periods 1, 2 and 3. The CBAR values indicate that a savings of 23, 68 and 84 cruzeiros would be obtained from a unit increase in capacity in each respective time period. The reduced level of demand in period 4 results in excess capacity in that period for the rail terminal. A total of 2.2 million tons of grain and meal arrive in Paranaguá by rail and approximately the same tonnage by truck. These figures correspond closely to actual arrivals in 1976, with differences due to estimation for slightly different time periods (GREMOS).

The terminal improvements suggested earlier are now included in the model. The decrease in turn-around time of 50 hours provides a minimum of 60% additional rail cars to users, based on the longest haul in the system (Maringá-Paranaguá).[8] The rail car capacity constraint is represented by the parameters in the terminal arcs rather than by creation of additional arcs and nodes. The C_{ij} value is again Cr$29/ton, based on the assumption that all savings in operating costs are applied toward the captial costs of constructing the new terminal. There is still a saving in total costs of Cr$26 million (not shown in the table) from the transfer of 447,000 tons of freight from truck to rail. Further, this modal transfer implies a considerable social benefit by alleviating the saturated conditions in Paraná's two-lane highways.[9] The reduction in turn-around time would reduce operating costs associated with terminal delays by Cr$23.75 per ton. This figure times 2.6 million tons yields an approximate operating cost reduction of Cr$63 million. The results suggest that by charging the same rates: (1) the railroad would have Cr$63 million savings annually to apply against the terminal construction costs; (2) there are additional direct benefits to grain shippers of Cr$ 26 million resulting from the modal shift away from more expensive truck transporation; and (3) there are substantial external benefits to other highway users from reduced truck traffic, which are not quantified in the model.

The zero CBAR values in the solution for the improved terminal indicate that rail car availability is no longer a binding constraint on the rail system. However, the rail line capacity is now reached on the mountain stretch during periods 2 and 3, representing costs of 30 and 64 cruzeiros to the system in those periods. Thus, improvement in these periods must await increases in actual rail line capacity, either by more adequate sidings or a new line. The optimal solution, however, indicates that 141 and 175 thousand tons of grain and meal are still being transported by truck in periods 1 and 4, respectively, even though the railroad has excess capacity in those periods. An examination of arcs not shown in Table 1 reveals that these shipments are from the areas nearest the port. Truck arrivals occur in these periods since congestion on the line hauls and in the terminal for trucks are much lower than during periods 2 and 3. In the actual system, the railroad transports a much greater proportion from the nearby locations than occurs in the optimal solutions of Table 1. This results from the railroad's attempts to secure cargo more uniformly throughout the year, and the resulting contracts with the crushing industries in nearby Ponta Grossa.

Implications

The network analysis reveals that the actual pattern of short rail hauls does not maximize savings to the transfer system, since the mountain haul is by far the most expensive line haul in the system, and incurs the same terminal operations as longer hauls. Thus, the rail corporation may also be suboptimizing, or maximizing cargo rather than revenue. Lower terminal costs with an improved terminal in Paranaguá, along with peak demand pricing, however, could improve the railroad's financial situation, while removing considerable tonnage from the congested highways in all time periods.

In the current Brazilian situation, flat rates are charged for shipments between terminals with no price incentives to users to upgrade their terminals on an individual or collective basis. The railroad faces, in turn, a severe budget restriction on upgrading its own terminals through its subsidiary storage corporation. Price incentives for trainload volume movements, peak demand pricing and lower operating costs associated with reduced turn-around times could benefit the rail corporation, reduce the grain shipping bill and alleviate highway congestion.

Although this analysis is specific to the Brazilian situation, the concepts have general implications for transportation pricing. Railroads have a limited monopoly on transportation services and tend to be regulated or state owned. This has led to the tendency on American railroads for price regulation to be based on average costs from different operations and rail companies, rather than the cost to the rail line in question of providing a specific service (Sward, pp. 8-24). The results in both the U.S. and Brazilian cases is a dulling of price incentives to users and rail companies to adopt trainload volume and unitrain terminals.

Recently, the Special Project Staff of the ICC recommended readjustment of the trainload volume rates on U.S. grain, alleging discrimination against domestic users, since only export bound shipments received the lower rates.[10] Actually, the rate differential arose because only export ports were equipped to handle the large volumes of grain at the receiving end. Thus domestic elevator operators with trainload volume loading capacity could not get the lower rates on shipments to domestic users. In such cases, a relevant question to be asked is if price incentives can be successfully used to upgrade receiving terminals serving the domestic market.

Footnotes

1. Cost per ton-kilometer is the cost of transporting one ton over a distance of one kilometer. Costs are calculated herein in Brazilian currency. In mid September, 1976, the official exchange rate was Cr$11.1 = U.S.$1.00.

2. This can be compared with the Ponta Grossa-Apucarana stretch with minimum radius on curves of 305 meters and a maximum grade of 1.2%, not excellent figures but useful as a yardstick for the difficulties of the Ponta Grossa-Paranaguá line.

3. As Sward points out, true unitrain operations avoid terminal and switching operations and use specialized equipment. The text uses the more general term "trainload volume movement" to refer to a trainload of a specific type of grain.

4. A number of export companies and one major cooperative have their own sidings in the port area. In general, they accommodate eight or fewer cars and thus require complicated switching operations.

5. The inclusion of intermediate nodes does not require any changes in the network solution procedures.

6. Until recently, the Fulkerson or "out-of-kilter" codes were considered the most efficient algorithms for solving network problems. Faster solution times have now been recorded with other network codes for some problems (Bradley; Fuller, Randolph and Klingman). The size of the network problems solved in this research precludes consideration of solution by non-network methods, but is not great enough to justify a search for the most efficient network algorithm currently available. The problems were solved using a Fulkerson code developed and generously made available by Howard L. Gauthier, Professor of Geography, The Ohio State University. The longest solution time recorded was 183 seconds, for an initial network of 502 arcs and 1,114 nodes with the sequential solution of 12 subproblems. A modest 120 K of storage space was required.

7. This requires the addition of a dummy arc connecting DD to DO in Figure 4.

8. Capacity would be increased more than this for shorter hauls. Some minor increases in rolling stock might be required for the longer hauls in the initial solution than actually occurred. The railroad could have met this by transfering some cars from other divisions, but had no incentive to do so since congestion in Paranaguá resulted in use of cars as surrogate storage.

9. The external economies were not calculated in the model, but are probably much greater than the value of savings to grain shippers (Wright, Appendix C).

10. The recommendation has apparently not been adopted.

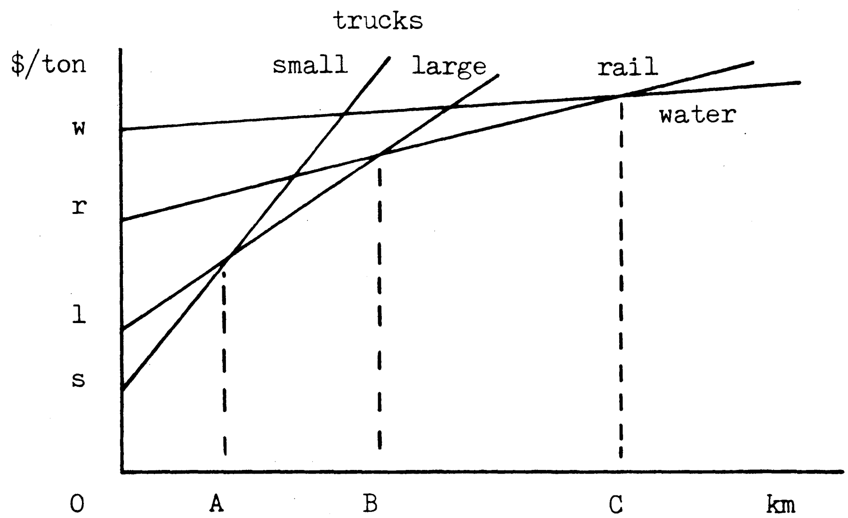

Figure 1. Distance determines economical modes when terminal costs are fixed.

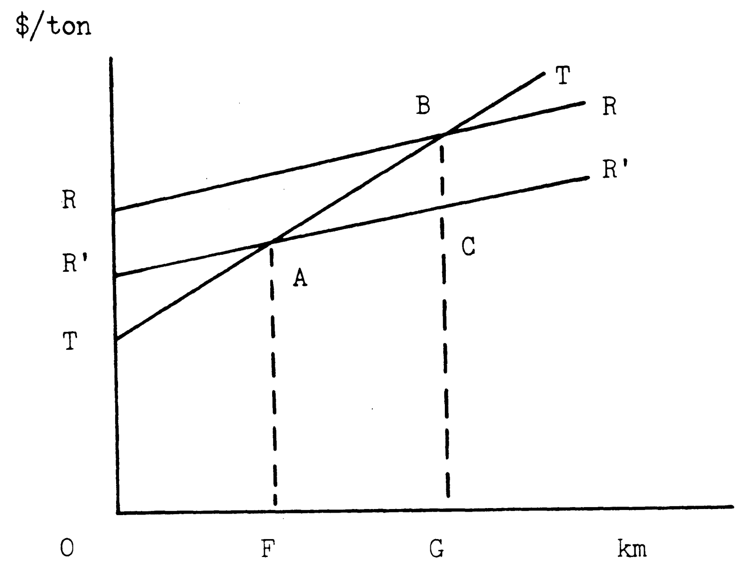

Figure 2. Modal shift with decreased turn-around costs

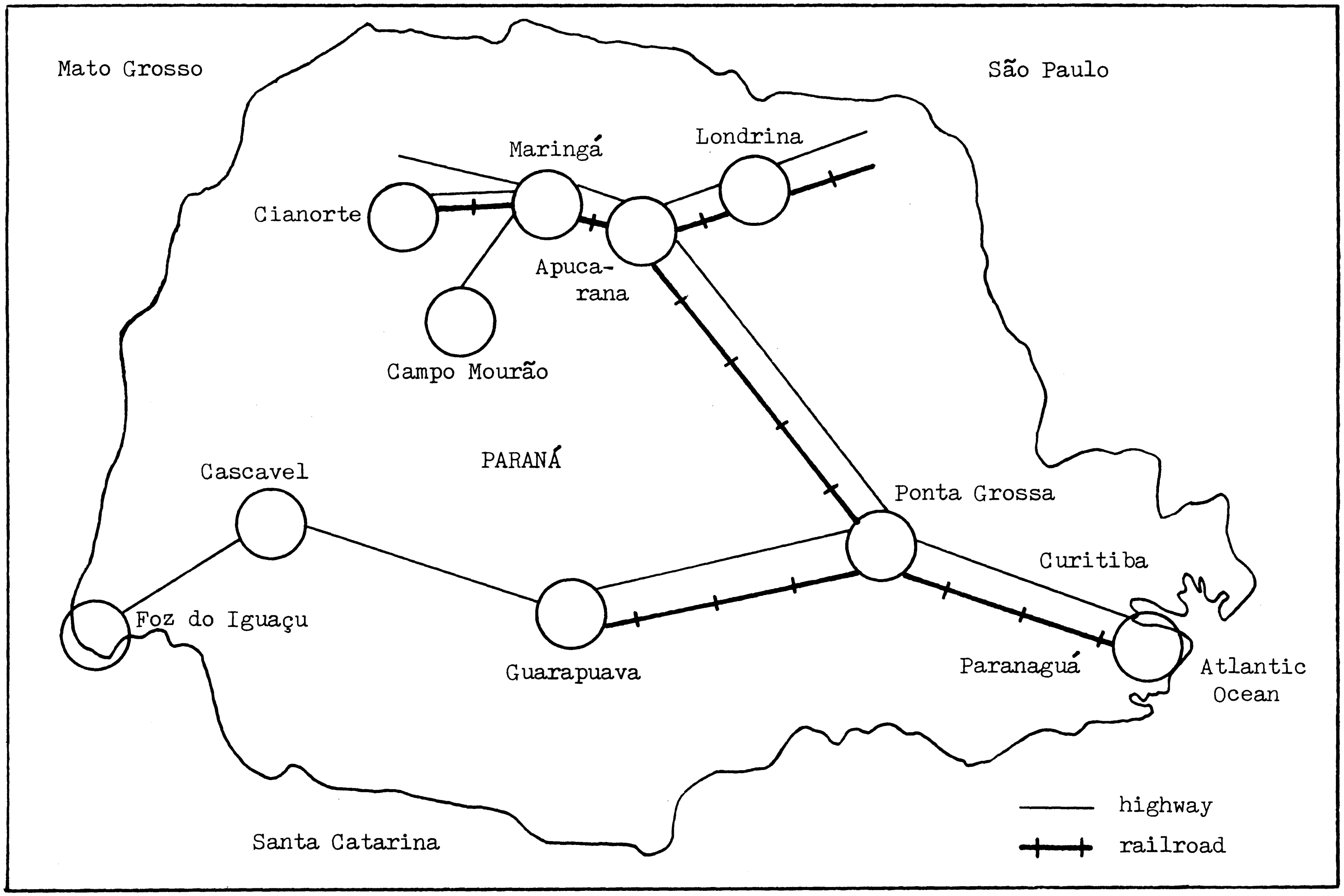

Figure 3. Principal rail lines and paved highways on the Paraná export corridor

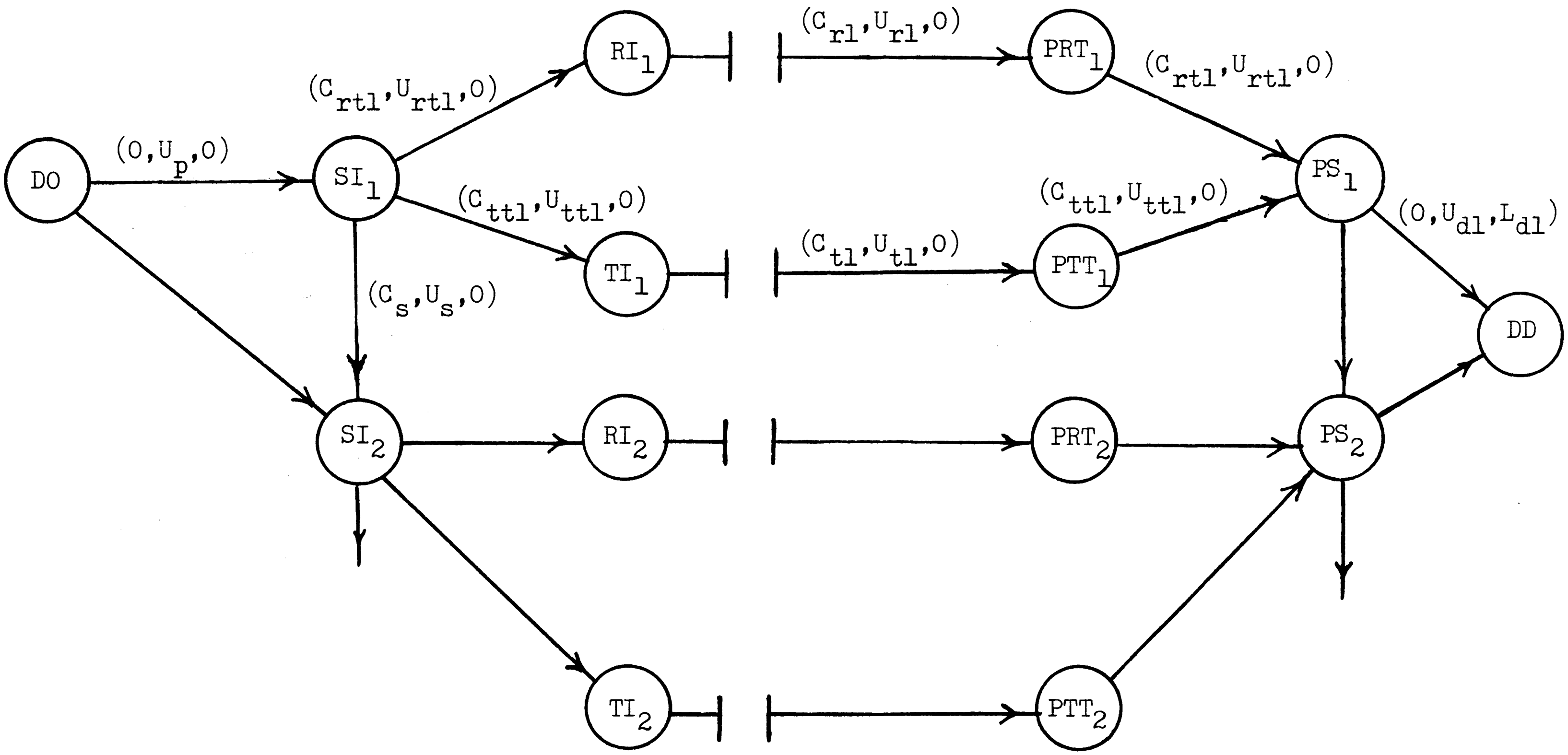

Figure 4. A schematic representation of the grain transfer network for the Paraná export corridor

Table 1. Partial listing of rail arcs for 1976 transfer problems, with modal split indicated

Location	Facility	Period	C_{ij}[a]	CBAR[a]	U_{ij}[a]	X_{ij}[a]	Truck Transportation[b] tons	modal shift	
			(Cr$/ton)		(1,000 tons)		(1,000 tons)		(%)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
(a) 1976 optimal solution to basic transfer problem									
Paranaguá	Terminal	1	29	-23	451	451	182	-	-
"	"	2	29	-68	462	462	587	-	-
"	"	3	29	-84	750	750	1,283	-	-
"	"	4	29	0	560	537	175	-	-
				Total:		2,200	2,227		
(b) Simulation of improved Paranaguá terminal									
Paranaguá	Terminal	1	29	0	720	475	141	41	23
"	"	2	29	0	737	625	442	145	25
"	"	3	29	0	1,196	1,011	1,022	261	20
"	"	4	29	0	895	537	175	0	0
				Total:		2,648	1,780	447	20
Mountain	Rail Line	1	21	0	608	475	141	41	23
"	"	2	21	-30	625	625	442	145	25
"	"	3	21	-64	1,011	1,011	1,022	261	20
"	"	4	21	0	756	537	175	0	0
				Total:		2,648	1,780	447	20

[a] C_{ij} is the arc cost of a unit of flow, CBAR the net arc cost, U_{ij} is the upper limit on flow, and X_{ij} is the flow over the arc in the optimal solution. The values of the lower limit (L_{ij}) for this table are all zero. Totals are subject to discrepancies from rounding.

[b] This is the tonnage arriving in Paranaguá by truck. Modal shift comparisons refer to the same time period of iteration 1 in part (a). The values in columns (8), (9) and (10) refer to the same time period as the rail arcs in columns (1) - (7), but are derived from the solution values for highway arcs not shown in the table.

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